INFLUENCE OF CHASSIS CONTROL SYSTEMS ON VEHICLE HANDLING AND ROLLOVER STABILITY

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ABSTRACT

In this paper the influence of active chassis systems, in particular Electronic Stability Control (ESC) and Active Rear Steer (ARS), on vehicle limit handling and rollover stability is examined through vehicle testing. Effectiveness of ESC systems in influencing rollover stability in the National Highway Traffic Safety Administration (NHTSA) dynamic rollover test is first evaluated. Since there is no generally accepted objective and repeatable procedure for evaluating and quantifying vehicle handling as it relates to safety, a process of developing such a test procedure is described. Vehicle handling tests used in the automotive industry are briefly reviewed. The criteria used for selection of maneuvers that show the best potential and can characterize these aspects of handling, which affect safety, are described. A subset of the most promising maneuvers is selected. A step steer maneuver and an open loop maneuver with steering reversal are further developed through simulations and vehicle testing. A preliminary handling metric is described, which balances the aspects of handling influencing safety. Test results for both handling tests are presented, which compare performance of vehicle with ESC and ARS systems enabled to a passive vehicle.

INTRODUCTION

In the last decade, popularity of vehicles with a high center of gravity in the United States, e.g., Sport Utility Vehicles (SUVs), gave rise to increased interest in studying vehicle rollovers and developing active safety systems capable of reducing the probability of this type of crash. While rollovers constitute only a few percent of all crashes, they rank disproportionately high among fatal crashes. For example, rollovers are responsible for about 25% of all traffic-related fatalities in the USA and about 60% of fatalities in accidents involving SUVs [1]. In response, automakers and suppliers pursue design changes, which could lead to improved rollover resistance without sacrificing utility of vehicles.

Recently, NHTSA introduced a dynamic rollover test as a part of the New Car Assessment Program (NCAP). In the test, a vehicle driven on a dry, smooth and level surface is swerved in a rapid succession in one, then the opposite direction. The steering input supplied by a robot is characterized by high rates and high amplitudes of the steering angle, in order to emulate steering input during an emergency road edge recovery maneuver [2]. It is possible that some design changes made in an effort to improve vehicle rollover resistance in this test may alter vehicle handling characteristics in a way that could adversely affect other aspects of vehicle safety. For example, for a vehicle with high center of gravity, rollover resistance in the dynamic test could be improved by reducing the maximum lateral acceleration or its rate of change. If done indiscriminately, this would limit the cornering ability or responsiveness of the vehicle in emergency maneuvers, both of which are important aspects of safety.

These types of design changes could be achieved with relatively minor effort for a vehicle equipped with an active chassis control system, such as an Electronic Stability Control (ESC). These systems permit vehicle designers to trade off vehicle responsiveness in limit cornering maneuvers against stability by specific tuning of the control algorithm. Since in most rollover crashes, drivers lose control of the vehicle prior to rollover, improving rollover resistance in the dynamic test may not help to prevent rollover from occurring if the improvement is achieved at the expense of emergency handling. The prime goal of this research is therefore the development of a better understanding of vehicle handling and rollover stability, especially for vehicles equipped with active chassis systems. The term handling is limited here to these aspects of vehicle response to driver steering and possibly throttle and brake inputs, which affects vehicle safety. Since there is no generally accepted, objective and repeatable test procedure that quantifies vehicle handling as it relates to safety, development of such test methodology has become an important goal of this study.

This paper is organized as follows. In the next section the vehicle used for testing, which is equipped with ESC and ARS (Active Rear Steer) systems, is briefly described. Then selected results of NHTSA dynamic rollover tests are presented to illustrate the ability of ESC system to affect vehicle roll stability and yaw response in this test. Subsequently, a brief review of widely used handling tests is given. Criteria for selecting the most suitable handling maneuvers for further development are outlined, followed by detailed development of selected maneuvers. The handling metrics are briefly discussed. Results of vehicle testing in two transient handling tests are presented for a vehicle with ESC and ARS systems. Finally, conclusions are presented.

TEST VEHICLE

The test vehicle used in this study is the Chevrolet Silverado pick-up truck with rear wheel drive shown in Figure 1.

Figure 1. Chevrolet Silverado test vehicle.

The vehicle is equipped to allow safe dynamic rollover and limit handling testing, and to record the data. Specifically, it is fitted with a roll cage, five point harness safety belts and front and rear outriggers. The load rack above the truck bed permits the safe addition of payload to increase the height of the center of gravity and vehicle roll inertia, if necessary. This provides a means of modifying the rollover stability of the vehicle. The vehicle is instrumented with a programmable steering robot to achieve precise and repeatable steering inputs. Three optical height sensors measure distances from the body to the ground on each side of the vehicle; from these measurements, the true body roll angle with respect to the ground can be derived. Optical sensors placed at all wheel hubs permit determination of wheel lift-off. In addition, suspension deflection sensors allow monitoring of the wheel positions relative to body. The vehicle is also instrumented with an optical sensor measuring longitudinal and lateral velocity with respect to the ground, a steering wheel angle sensor and an instrumentation-grade, six-axis inertial sensor. Two active chassis systems are available on the vehicle: a brake-based ESC system and an ARS system, which can be selectively disabled, if desired. Both of these systems include additional sensors; for example, the rear wheel steering angle, brake caliper pressures at all four corners and wheel speeds are measured. Each active system can be disabled, if desired.

Vehicle performance was also evaluated using a high-fidelity vehicle model, which includes models of active systems and associated control algorithms. The model was validated against the test data. Details of the model are beyond the scope of the paper and are not presented here. In addition to the Chevrolet Silverado, a vehicle with an active stabilizer bar system was used for this evaluation, but the results are not presented here. A detailed description of this vehicle and the simulation model can be found in reference [3].

EFFECT OF ESC SYTEM ON VEHICLE PERFORMANCE IN DYNAMIC ROLLOVER TEST

In this section the influence of ESC system on vehicle performance in the dynamic rollover tests is discussed and selected test results are presented. As described in the introduction, the dynamic rollover test, also referred to as a fishhook test (since vehicle path in this test has a shape similar to a fishhook), is a severe steering maneuver, which involves a rapid reversal of the steering angle. This induces a large and rapid change in lateral acceleration from a peak value in one direction to the opposite, which heavily excites vehicle roll motion. The vehicle fails the test if it experiences a Two Wheel Lift Off (TWLO) of at least 5 cm (2 in.). The details of the test procedure are given in a NHTSA report [2]. Any active chassis control system, which can reduce vehicle roll angle or lateral acceleration or even the rate of change of these variables during this test, can significantly affect the outcome. Examples of such systems are the ESC system and active stabilizer bar system. ARS system, which can steer the rear wheels as a function of the front steering angle and speed, has a lesser effect in this test.

The ESC system improves limit handling and stability of the vehicle by correcting severe understeer and oversteer conditions through active control of individual wheel brakes. The system uses the measured steering wheel angle and vehicle speed to determine the desired response of the vehicle in terms of yaw rate and sometimes vehicle sideslip angle or sideslip rate. It then compares the desired states with the measured (yaw rate) or estimated (sideslip angle) ones; when a sufficient discrepancy is detected, the system applies brakes to reduce the difference. By tuning the desired response and the control gains, vehicle designers can affect the balance between vehicle responsiveness and stability. For example, by reducing the magnitude of desired yaw rate or by more aggressive control of sideslip state (at the expense of yaw rate), a more stable response of the vehicle in transient maneuvers can be achieved. This tuning of the system can reduce vehicle rate of response and possibly peak lateral accelerations in fishhook tests, thus improving vehicle resistance to rollover. To illustrate, the results of two Fishhook tests performed at 75 km/h are shown in Figures 2 and 3.

In both cases, extra payload of 400 lb (182 kg) was placed at the load rack to increase tendency of vehicle to tip up during tests. The roll angle was limited to about 15 degrees by outriggers. The ARS system was disabled.

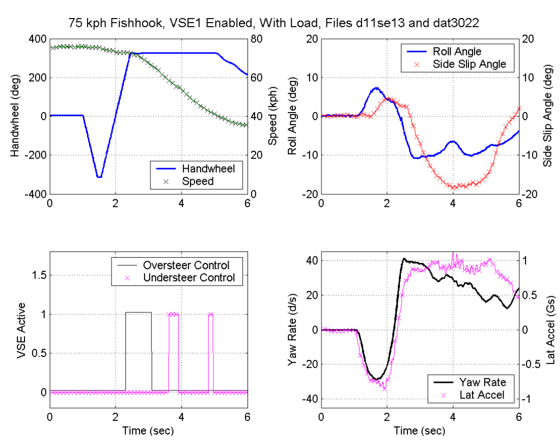

Figure 2. Fishhook test at 75 km/h with ESC system in configuration 1.

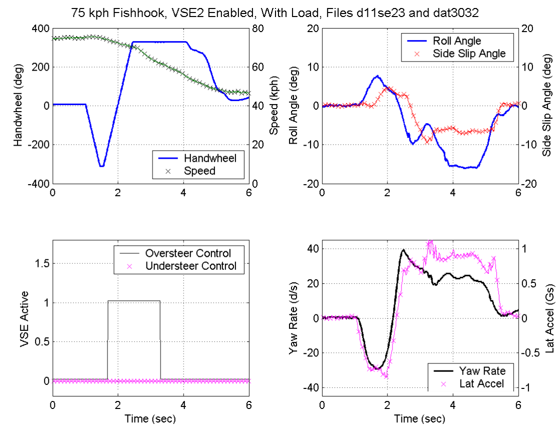

Figure 3. Fishhook test at 75 km/h with ESC system in configuration 2.

In the maneuver illustrated in Figure 2, tuning of ESC system (configuration 1) was representative of many other light vehicles, whereas in Figure 3 (configuration 2) tuning was modified to further restrict oversteer condition by reducing the maximum values of yaw rate and sideslip states. It is seen that during and immediately after the quick transient phase, the ESC 2 system activates earlier and provides correction for a longer period of time. This results in lower vehicle sideslip angle and temporary reduction in vehicle roll angle, yaw rate and lateral acceleration. After the brake intervention subsides, however, the roll angle increases again and is not corrected by the ESC system, since the system is designed to manage yaw plane motion, which is now close to the desired motion. It should be noted that in the same maneuver performed with ESC system disabled (not shown here), the vehicle reached the roll angle corresponding to the outrigger contact immediately after the reversal in lateral acceleration.

It can be concluded that the ESC system has the capability to affect the roll response of vehicles in the Fishhook test, especially in the transient phase of the maneuver, by changing the tuning parameters in the control algorithm. These changes, however, affect vehicle response in the yaw plane by changing yaw rate, sideslip angle and lateral acceleration responses, which are important characteristics of handling. It is therefore desirable to develop a test procedure to evaluate vehicle handling in addition to rollover propensity, so that vehicle performance and stability in the yaw and roll planes can be evaluated comprehensively.

MANEUVER SELECTION FOR HANDLING EVALUATION

In this section, the process of selecting maneuvers, which could be used to objectively evaluate the handling behavior of vehicles, is described. Vehicle handling is a complex and highly subjective characteristic with many different aspects. In this study, emphasis is on the aspects of handling performance, which affect safety. Of particular interest are the handling properties in the non-linear range of handling and at the limit. There are several reasons for this. First, vehicles often reach the limit handling range in emergency avoidance maneuvers; thus, it is of prime importance in crash avoidance. Second, controlling vehicles at the limit is generally more difficult for a typical driver than in the linear range of handling. Most drivers are accustomed to operating their vehicles in the linear range (normal driving) and do not have experience in controlling vehicles at the limit. Third, since tire forces are limited by surface friction, vehicle handling typically deteriorates as the limit of friction is reached. For example, in handling tests performed by Consumer Union [4] the routine handling score was either better or at least the same as the emergency handling score for all of 141 vehicles evaluated in this publication. Thus, one can expect that good emergency handling guarantees that routine handling would be at least as good.

ASPECTS OF HANDLING AFFECTING SAFETY

The objective here is to establish a test procedure to evaluate and quantify these characteristics of handling, which affect safety. The following are aspects of handling, which in the authors' judgment affect safety:

- **Turning ability** – is an ability of the vehicle to turn sharply in emergency maneuvers; therefore, the maximum lateral acceleration and quickness of achieving it are both important.

- **Graceful degradation at the limit** – there should not be a large or sudden change in vehicle behavior when limit of adhesion is reached. Essentially, this requires a progressive increase in vehicle understeer as lateral acceleration increases and no rear breakaway, implying small sideslip angle.

- **Predictability** – predictable and progressive response to driver inputs with no or minimal need for corrections. It requires good correlation between the driver input and vehicle response in the entire range of operation. Vehicle response should be well damped with no or minimal overshot and oscillations (otherwise frequent driver corrections are necessary). Time delays between the input and outputs should be consistent and not too large.

- **Responsiveness** – requires quick response to driver inputs in terms of both initial delay and the total response time and sufficient static gain between the input and the output (e.g. yaw gain).

- **Stability** – not only should the vehicle response to bounded inputs remain bounded, but also certain stability margins should be maintained in both steady state and transient maneuvers. For example, the vehicle should maintain understeer characteristic with limited sideslip angle and no sustained oscillations in transient maneuvers.

It is noted that there exists some overlap among the desired handling characteristics described above. For example, vehicle response must be stable in order to be predictable; reasonably short time delays are required for good responsiveness and predictability and so on.

There exist other characteristics, which are often considered aspects of handling, which are not included in the above list because they either are too subjective or have little effect on safety. These include: on-center steering feel, steering wheel vibration, and steer torque feedback. Ability of the vehicle to reject disturbances, such as due to aerodynamic forces (e.g. side wind), road inclinations or road roughness, is not explicitly included, but it is implied by stability and predictability.

COMMONLY USED HANDLING TESTS

Since there is no general agreement on which handling tests provide the best assessment of handling behavior, many different tests are used by the automotive industry. In general, they may be roughly divided into the following categories:

- Open loop tests, which determine vehicle characteristics in response to specified control inputs.

- Closed loop task performance tests, which determine performance of driver-vehicle combination in a specific driving task.

- Subjective assessment, in which drivers evaluate handling behavior by driving a vehicle over a test track and a set of maneuvers.

The test maneuvers may also be divided into steady state and transient tests, dependent on whether they seek an assessment of steady state or transient properties. Since objectivity and repeatability of test procedure are very important considerations, the subjective assessment, in which both maneuver selection and evaluation are driver dependent, is not considered in this study. From this point of view, closed loop task performance tests have also disadvantages of being driver dependent to some extent and having a tendency to mask the effects of vehicle characteristics since drivers adapt their inputs to vehicle response. However, it is possible to define a reasonably objective index of performance in these maneuvers if measures of task performance are combined with a measure of driver steering effort.

Below, the most common types of handling tests are briefly reviewed. Many of them are either standard maneuvers adopted by SAE or ISO or proposals of standard tests by these organizations.

Slowly Increasing Steer Test (Skid Pad Test)

This test evaluates the steady state handling in both linear and non-linear ranges of operation. There are three forms of this test: constant speed, constant steer, and constant radius. A slowly increasing steer maneuver, in which the steer angle is slowly increased at constant speed, is described in SAE Standard J266 [5]. In another version of the test, a constant steer angle is maintained, but vehicle speed is gradually increased. In a steady state circle maneuver, a constant radius of turn is maintained, while both steering angle and speed are slowly increased [6].

Step Steer Test

A steer input in the form of a step function is applied at a specific speed to produce a specific lateral acceleration. An example is the ISO standard 7401 [7]. This test characterizes transient response of the vehicle, but includes a steady state portion as well. Therefore, quickness of vehicle response to the steering input in terms of yaw rate or lateral acceleration can be quantified. Similarly, variables related to vehicle stability, such as overshoot in yaw and roll responses, can be determined.

Braking in Turn Test

In this test, brakes are suddenly applied in a steady state turn of specified lateral acceleration, as described for example in the ISO/DIS 7975 standard [8]. This test primarily evaluates vehicle stability and predictability, in particular sensitivity of vehicle yaw response to disturbance in the form of braking and associated load transfer.

Dropped Throttle in a Turn

In this test, a vehicle is in a steady state turn with a pre-determined level of lateral acceleration, for example 90% of the maximum acceleration that vehicle can develop on a dry surface. The driver initially applies throttle in order to maintain speed. The throttle is then suddenly released. Similarly to the brake in turn test, this test evaluates vehicle stability and predictability in response to the change in longitudinal tire forces. This test maneuver is detailed in ISO Standard 9816.

Open Loop Test with Steer Reversal

In this test, a steering input is applied which has a pattern similar to that experienced either in a single lane change or a double lane change maneuver. This test demonstrates vehicle response in maneuvers involving steering reversal. This is important, because some vehicles may be stable in a step steer maneuver, but may be difficult to control in maneuvers involving steer reversals, especially when performed at the limit. An example of this type of test is a transient response test with the steer angle being one period of a sinusoid (a pseudo single lane change test) as described in the ISO/TR 8725 proposal [9]. Another example is a pseudo double lane change test proposed by NHTSA [2], in which the steering pattern is an averaged driver steer input in several closed loop test maneuvers. In some variants of the test, the steer input can have rectangular (stepwise) or trapezoidal pattern, which may be more demanding due to the sudden changes in the steer input.

Steer Reversal with Driver in the Loop

In this test, a vehicle is driven through a path determined by cones. The most common types of this test are: single and double lane changes and a slalom. In a single lane change test, the path defined by cones may represent a quick single lane change. A more frequently performed version of this test is the one in which the vehicle is driven straight at a specific speed towards an obstacle (a row of cones) requiring a lane change to either side. The driver is told as late as possible whether to go left or right. The main measure of performance in the test is the shortness of time or distance to the obstacle when the avoidance maneuver can be performed without striking the cones. This is a typical task-performance test, in which the outcome is determined by the driver-vehicle system.

In a double lane change test, the path simulates a maneuver, in which the vehicle quickly changes lanes (e.g. to avoid an obstacle) and then returns to the original lane. The most widely used test procedure is that defined by ISO/DIS Standard 3888 [10]. In this procedure, the course is strictly defined, giving the driver very little freedom in selecting the path. The width of each lane is defined as a function of vehicle width. The main result of the test is the maximum possible speed of entry at which the test can be completed without striking any cones.

In the slalom test, the vehicle is driven as quickly as possible on alternating sides of a series of cones. Large lateral acceleration is generally achieved. This test has been criticized on several grounds. The path of the vehicle and the steer pattern are not likely to occur in real world driving. Furthermore, the comparative ranking of vehicles may depend on spacing of obstacles due to different natural frequencies of yaw and roll modes for different vehicles. This last problem can be mitigated by relating the timing (and spacing) of turns to the natural frequency of the yaw mode, if it exists (e.g. if the yaw mode is not over-damped at the speed at which the test is performed).

Frequency Sweep Test

This test is performed primarily to quantify vehicle handling response to a steer input that covers a significant range of frequencies, with one of the main objectives being obtaining a frequency response characteristic of the vehicle. This can reveal, for example, a resonance frequency in vehicle yaw response, which may lead to instability under harmonic steer input at that frequency. Quickness of vehicle response can also be measured in this test. Two most common examples of these tests are a steering harmonic sweep test, in which the steer input is a harmonic function but with a slowly increasing frequency and the pseudo-random test as described in the ISO 8726 proposal [11]. This test is usually performed within or close to the linear range of handling.

Impulse Steer Test

In this maneuver, a vehicle is driven straight at a specific speed when a sudden steer input is generated with prompt restoration to straight ahead. This test demonstrates transient response of a vehicle in response to a sudden disturbance. It can also be used to generate frequency domain characteristics using Fourier transform methods.

CRITERIA FOR SELECTION

Among the test maneuvers described, there are some that do not characterize vehicle handling at the limit and therefore are inadequate for our purposes. There remain, however, several tests, which reveal similar aspects of handling performance or may even have similar steer patterns. In order to reduce the number of maneuvers, it is necessary to specify the criteria for selection. The criteria used here are listed below. Many of them are similar to those used by NHTSA in selecting the dynamic rollover test.

- **Objectivity and repeatability.** The outcome should be independent of the personnel performing the test, as long as the test procedure is being followed. The results should be repeatable for the same vehicle, so that they can be reproduced.

- **Feasibility** (ability to perform). This category describes how easy/difficult (or expensive) it is to perform the test. For example: is it time-consuming, does it require expensive instrumentation, special test track facility, a lot of effort (e.g. many iterations), etc.

- **Completeness** (handling metric measurement capability). This category describes how many aspects of vehicle handling performance can be evaluated in one test and how many metrics that quantify vehicle handling can be determined from the test data. The most important aspects of handling are those that affect safety, as listed in the previous section.

- **Realistic character of the test.** This is an evaluation of whether the test has field relevance. That is whether or not it is similar to maneuvers performed by actual drivers, especially in emergency situations. Similarities to standard tests proposed by SAE, ISO or frequently used by automakers may also be taken into account.

- **Discriminatory capability.** Describes how effective the test is in capturing significant differences in vehicle handling qualities. It is not desirable to have the metrics derived from the tests performed on different vehicles to be clustered in the narrow range of values, especially when the differences are close to measurement errors.

Note that conflicts among the above criteria may exist. For example, requirements of objectivity and repeatability, implies that the results should be robust with respect to very small changes in parameters of vehicle, chassis or tires. This is somewhat in conflict with the requirement of discriminatory capability.

Using the above selection criteria, all types of maneuvers were ranked and the top three receiving the highest scores were selected for further development. They are as follows:

- Slowly increasing steer (skid pad) test
- Step steer test
- Open loop steer reversal test.

All selected maneuvers are open loop, in which a steering input can be performed by a robot. This provides a significant advantage over closed loop maneuvers in the area of objectivity and repeatability, but also in discriminatory capability, because human drivers can compensate for handling differences. The slowly increasing steer test reveals steady state handling characteristic and provides reference points for other tests, as will be discussed later. The step steer test provides both transient and steady state characteristics. The open loop steer reversal test is generally more demanding than the step steer test because vehicles are more prone to become unstable and spin out in this test. The steering pattern can resemble those experienced during emergency single and double lane changes.

DESCRIPTION OF SELECTED HANDLING TEST MANEUVERS

The selected maneuvers were further studied through vehicle testing and simulations using a validated model of a vehicle. The purpose was to determine the exact steering patterns, including steer rates and amplitudes, and entry speeds.

Slowly Increasing Steer Test

This test is well defined and is currently performed by NHTSA as part of dynamic rollover test procedure [2]. The maneuver is performed with a constant speed of 50 mph with steering angle ramping up at a rate of 15 degrees per second or less (NHTSA uses 13.5 deg/s). Since our goal is to reach the friction limit for some time in this test, the steering angle is increased up to 360 degrees or to the angle corresponding to the wheel lock position, whichever is smaller. The steering pattern is illustrated in Figure 4.

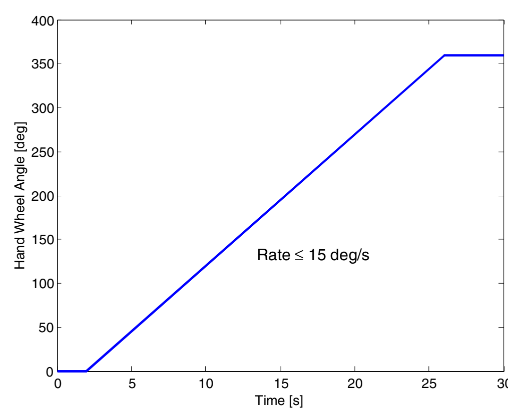

Figure 4. Steering pattern in slowly increasing steer test.

In addition to characterizing steady state response of the vehicle, this test provides characteristic values for the other tests and for determining performance goals in transient tests. For example, the steering angle amplitudes in the transient tests are the multiples of the steering angle corresponding to 0.3 g of lateral acceleration in this test.

Step Steer Test

In this test, the general steer pattern is well defined. In order to determine the entry speed, steering angle amplitude and rate of change during transient, series of simulations and vehicle testing were performed. In simulations, vehicle speed varied from 35 to 90 mph, the steering angle amplitude from 30 to 360 degrees and steering rate from 500 deg/s to 2000 deg/s. The purpose was to determine the values that make the maneuver severe enough to reveal potential weakness in emergency handling, yet still appear realistic. It was found that vehicle response deteriorated with increasing speed, primarily by becoming more oscillatory, but safe speed for testing was found to be about 60 mph. Vehicle response also deteriorated with increasing steering angle, but only up to a certain value of the steering angle (which depended on speed). Vehicle response did not change significantly when the steer rate increased from 1000 to 2000 degrees per second. Consequently, the following parameters were selected for the step steer test:

- speed of entry 55 mph
- amplitude of steer angle 5 times the steering angle corresponding to 0.3 g of lateral acceleration in the slowly increasing steer test
- steer rate of 1000 degrees/second
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The steering pattern is illustrated in Figure 5. The driver does not apply the throttle during the maneuver.

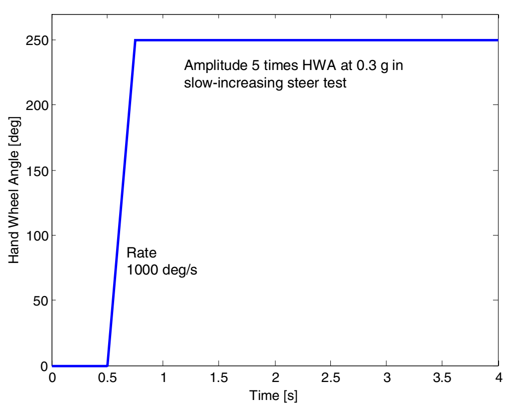


Figure 5. Steering pattern in step steer test.

Steer Reversal Test

The maneuvers with steer reversals considered here are the open loop pseudo lane change and open loop pseudo double lane change. These maneuvers, when performed at the limit, can be very challenging, in particular when reversals of steering angle are quick. When the steering angle of the front wheels is suddenly reversed, the front tire slip angles and consequently the front tire lateral forces are reversed, while the rear axle lateral force lags, maintaining the direction supporting the first turn. As a result, the vehicle is, for some time, subjected to a pair of opposite lateral forces, which creates a large yaw moment causing a rapid rotation of the vehicle. This generally yields large overshoot in yaw rate and the development of a significant sideslip angle. In this type of maneuver, the timing of steering reversal(s) and the rate of change of steering angle have a very important influence on vehicle performance.

Several choices had to be made in developing the steering pattern for this test based on a validated simulation model for the test vehicle. First, a trapezoidal pattern was selected in favor of rounded one. While rounded, e.g. harmonic, pattern resembles the actual driver steering in emergency situations more closely, it poses difficulties in proper timing of steer reversal and generally provides less severe excitation of vehicle yaw motion than the trapezoidal steering of the same amplitude. Second, the steer pattern with two reversals, rather than one, was selected because it includes the latter, was found to provide more severe excitation and is in fact more akin to the steering patterns in emergency lane changes. Third, the time of initiation of each steering reversal was chosen to coincide with the peaks of vehicle yaw rate. This selection was found to provide the worst, or very close to the worst, response of vehicle in terms of stability. This timing is chosen to match the natural yaw response of vehicle, unlike in the fixed steering pattern, which could be criticized on the grounds that it may excite yaw modes of some vehicles more than others. The steering amplitude and rate were selected at the level observed in emergency lane changes performed by a human driver at the same speed. The chosen steering pattern is illustrated in Figure 6.

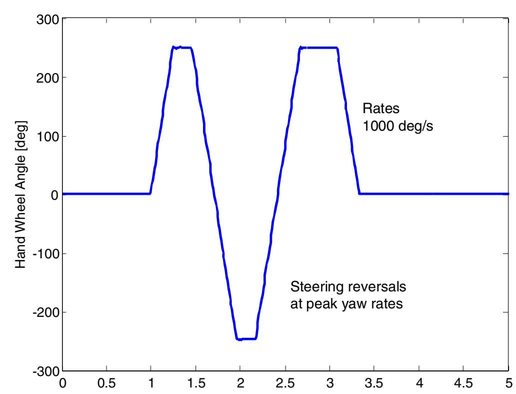


Figure 6. Steering pattern in steer reversal test.

The entry speed for this maneuver is 55 mph, the amplitude of steer angle is 5 times the steering angle corresponding to 0.3 g of lateral acceleration in the slowly increasing steer test, and all steer rates are 1000 deg/s. Note that the dwell time of the steering angle increases significantly in the last phase of maneuver as the lag in yaw response of vehicle to the steering input increases. No throttle is applied during this maneuver.

HANDLING METRICS

Vehicle design involves many compromises from the point of view of desired handling properties. The main trade off is between vehicle responsiveness to steering input and stability or predictability. In addition, large stability margin in steady state conditions, as expressed by understeer gradient, may compromise cornering ability (since front tires saturate well before the rear axle reaches the limit lateral force) and may lead to oscillatory response at high speeds, since the damping ratio of the roll mode decreases as speed increases at a rate proportional to undesteer gradient [12]. In this section, a composite metric of vehicle performance is discussed. It should balance measures of several aspects of handling, which affect safety, as discussed earlier, and should include those aspects, which are difficult to reconcile.

Vehicle handling is usually evaluated in terms of vehicle response in the yaw plane as characterized by lateral acceleration, yaw rate and sideslip angle. It is known [13], however, that in the closed loop task performance tests the roll motion of vehicle, including both roll angle and roll rate, has a very significant effect on overall subjective rankings of vehicle handling. The main reason is that the driver steering control input, that is necessary to perform a difficult handling task (e.g. a quick lane change simulating an evasive maneuver), may be compromised if the vehicle exhibits substantial and poorly damped roll responses to rapid steering inputs. The secondary reason is that a driver continuously uses preview information about the path of travel to determine the necessary steer input for a given task. Changes in vehicle attitude, such as excessive roll motion, make this task more complicated. Thus, excessive and underdamped roll responses to rapid steering inputs should be penalized in the handling metric.

It is noted that several essentially identical performance measures can be used to describe different handling qualities influencing safety. This is because there is some overlap in the defined handling categories (for example, stability is necessary for predictability), but also there exists correlations among various metrics (for example, time delays tend to increase as tire sideslip angles increase). The following measures of performance are proposed to quantify various aspects of handling:

1. Measure of maximum lateral acceleration and quickness of achieving it.
2. Measure of oscillations in yaw response in transient maneuvers (yaw response overshoot in step steer, amplitude ratio(s) of yaw response in steer reversal test).
3. Measure of time delays in vehicle lateral response (time delays between steer angle and yaw rate and lateral acceleration in transient maneuvers, time delays between yaw rate and lateral acceleration in transient maneuvers).
4. Measure of lateral stability as expressed by rear axle slip angles (maximum slip angles or slip rates).
5. Measure of roll angle response (peak roll angle in step steer and steer reversal tests, peak roll rate, roll gain, roll angle overshoot in step steer test)

The rear axle slip angle was selected as a measure of vehicle stability, rather than the vehicle slip angle, since it is a more direct indicator of tire slip at all speeds and is less dependent on vehicle dimensions. Each of the above performance measures can be quantified, and a composite index can be constructed, which is a weighted sum of all components.

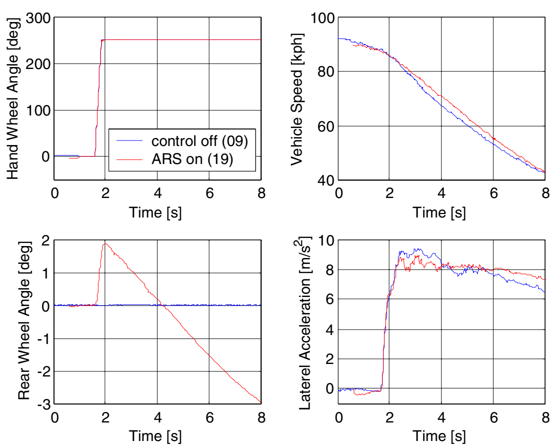
TEST RESULTS

In this section, selected results of vehicle testing are presented for two transient handling tests: step steer maneuver and the open loop double lane change test.

Step Steer Maneuver

Step steer maneuvers were performed multiple times for four different vehicle configurations: passive vehicle, vehicle with ESC system enabled, vehicle with ARS system enabled and vehicle with both ESC and ARS systems enabled. In this maneuver, the ESC system did not become active, primarily because the passive vehicle was stable and well controlled in this test. Therefore, the results with ESC system enabled are the same as with the system turned off and are not shown here.

The results obtained in a right turn for a passive vehicle (test 09) and a vehicle with ARS on (test 19) are illustrated in Figure 7. In both cases, the initial speed was nearly identical. However, the vehicle with ARS system enabled maintains a higher speed throughout the maneuver because of reduced losses of energy due to tire sideslip. The rear wheel steer angle depends on the hand wheel angle and vehicle speed and is initially of the same sign as the front steering angle, then of the opposite sign, with the sign change occurring at about 40 mph (65 km/h). The magnitude of the rear wheel steering angle does not exceed 3 degrees in the recorded portion of maneuver, yet the effects are quite dramatic. In particular, the overshoots in yaw rate and rear tire slip angles are almost entirely eliminated.



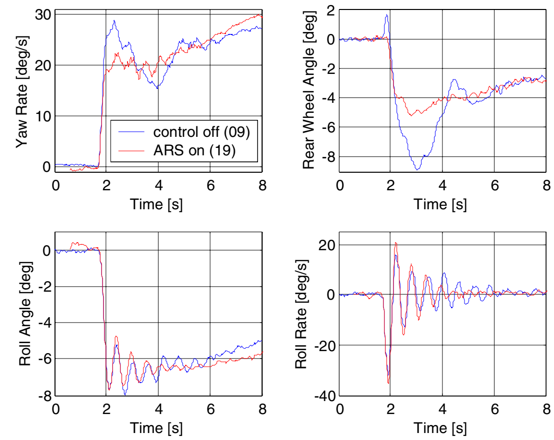


Figure 7. Comparison of vehicle responses in open loop step steer maneuver for passive vehicle and vehicle with ARS system enabled.

The peak value of rear tire slip angle is reduced from 8.9 to 5.2 degrees (a reduction of over 40%) and the first peak in yaw rate is suppressed from about 28.8 to 22.5 degrees/second. Lateral acceleration response is reduced by about 0.5 m/s^2 in the first two seconds of maneuver, as compared to the passive vehicle. The peak roll angles are about the same in both cases, but the peak roll rate is slightly higher in the case of the vehicle with the ARS system enabled. This is most likely due to slightly faster initial lateral acceleration response. The roll response, however, is better damped when the ARS system is enabled, primarily because of slightly lower lateral acceleration at the limit. Overall, the changes in roll response brought about by the ARS system were very small.

This example test result highlights the importance of having a composite index of handling that balances all the important, but often conflicting, aspects of performance. The ARS system significantly improves yaw response in terms of both speed of response and stability, but it reduces maximum lateral acceleration slightly.

Open Loop Double Lane Change

Open loop double lane change maneuvers were performed with passive vehicle and vehicle with ESC system enabled. In Figure 8, the importance of appropriate timing of steer reversals in this maneuver is illustrated. Here the results obtained in two open loop double lane change maneuvers for a passive vehicle are shown. Both were performed at the same entry speed, with the only difference being the dwell times in the last steering input, which were 0.3 second and 0.4 seconds, respectively. In the former case, the last steer angle reversal occurred before the yaw rate reached maximum value; while in the latter the steer reversal coincided with the peak yaw rate. Since after about 5.5 seconds the driver provided a very large steering correction in the second case, the traces beyond this time should be disregarded. The differences in vehicle responses are quite dramatic, with the vehicle reaching much higher peak values of rear axle sideslip angle, lateral acceleration, roll angle and slightly higher yaw rate in the maneuver, in which the last steer reversal coincides with peak yaw rate (dotted line).

In Figure 9, vehicle responses in open loop double lane changes are compared with the ESC system on (test 22) and off (test 19). The ESC system is activated shortly after the first steering reversal, as shown by the red line in the left top plot box. The system has a small effect on the second peaks in yaw rate, lateral acceleration and rear axle slip angle. In the final phase of the maneuver, however, the peak values of all three variables are reduced. The most pronounced effect is observed in rear axle slip angle response. For example, the peak value is reduced from 19.1 degrees for passive system to 13.8 degrees for vehicle with the system on. Delays in vehicle lateral acceleration and yaw rate responses are also significantly reduced in the last phase of the maneuver, making vehicle response more predictable. It should be noted that the ESC system used in the tests described here was operating in a less aggressive mode, tuned for non-obtrusive operation and referred to as configuration 1 in the second section. At the completion of the maneuver, the differences in vehicle speed between the tests with system on and off are only about 4 km/h, indicating relatively mild brake interventions. Note that the ESC system tuned in this manner improves significantly several aspects of handling performance without significant trade off.

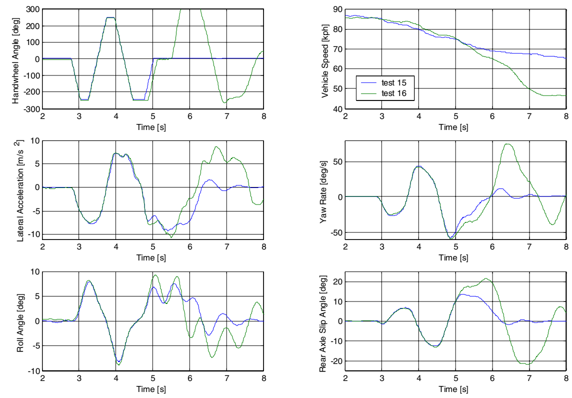


Figure 8. Vehicle responses in two open loop double lane change maneuvers performed with different timing of last steer reversal.

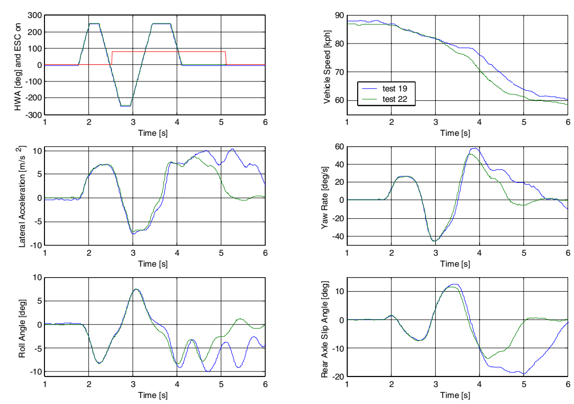


Figure 9. Vehicle responses in two open loop double lane change maneuvers performed with ESC system on (test 22) and off (test 19).

CONCLUSIONS

In this paper, a process used for development of an objective and repeatable test procedure to evaluate vehicle handling is described. Three open-loop handling tests are proposed, which may be used to evaluate the aspects of handling which influence safety. These tests, along with the dynamic rollover test proposed by NHTSA, are used to evaluate the effects of two active chassis systems on handling and rollover stability. The active chassis systems used are ESC and ARS systems. The following conclusions can be derived from this study: 1) tuning of ESC system can have a significant effect on vehicle roll response in the dynamic rollover test; 2) for some vehicles, a step steer test as described in this paper may not be severe enough to activate the ESC system; if showing the effect of ESC is a desired goal, an alternative test may be considered; 3) the ARS system can significantly improve most aspects of vehicle handling performance in the step steer test; 4) the open loop double lane change test is more demanding than the step steer test or an open loop single lane change test performed at the same speed and steering angle; 5) timing of steering reversals is very important in the open loop double lane change; for the vehicle tested here, the initiation of reversals, which coincided with peak yaw rates, rendered the least stable yaw response of vehicle; 6) an ESC system can significantly improve vehicle yaw stability and responsiveness in the second phase of the open loop steer reversal test, without adversely affecting other aspects of handling performance.

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